



Agricultural innovation and climate change policy in the Brazilian Amazon: Intensification practices and the derived demand for pasture

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ABSTRACT

Tropical deforestation in Brazil is a major source of greenhouse gas emissions that contribute to climate change. Brazil has taken several steps to reduce emissions associated with deforestation including the development of policies to promote and reward cattle ranching intensification. Intensification practices are hypothesized to reduce the conversion of tropical forests while simultaneously increasing the productivity of ranching on current pasture lands. This paper assesses the impact of intensification on the demand for productive land. A theoretical model of land use, which considers the degree of intensification in the estimation of the derived demand for pasture, is tested with data from small-scale landowners who operate dairy farms and calving operations in the greater Ouro Preto do Oeste region of Rondônia. Results suggest different trajectories for beef and dairy production. The intensification of cattle production exhibits a nonlinear relationship with the demand for productive land: first as farms become more intensive the demand for newly cleared land increases, but then decreases with further intensification. The results are different for dairy intensification, which is found to be correlated with reduced deforestation. Findings suggest that the reliance on policies that promote intensification can be a risky way of achieving climate change objectives.

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1. Introduction

Tropical deforestation in Brazil is a major source of greenhouse gases that contribute to climate change. Evidence suggests that further advances of the deforestation frontier will impact the global carbon cycle (Coe et al., 2011; IPCC, 2007; Malhi et al., 2008; Nepstad et al., 2008). Brazil's climate commitment reflects these concerns and includes plans to reduce emissions to 45% of 2005 levels by 2030 (UNFCCC, 2015). Because deforestation accounts for up to 70% of Brazil's greenhouse gas emissions (FAO, 2010), this commitment is largely premised on the possibility to slow, and eventually end, deforestation. Several policy levers suggested to meet these objectives are linked to cattle ranching, the greatest contributor to Amazonian deforestation (Bowman, 2016; Bowman et al., 2012; Bustamante et al., 2012). These policies are designed with the intent to achieve the dual goals of reducing the conversion of tropical forests to pasture and increasing the productivity of cattle ranching activities (Nepstad et al., 2014). For example, the 2004 Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) and Brazil's National Plan for Climate Change (NPCC) create specific targets for reducing land area devoted to

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extensive cattle ranching by protecting more than 25 million acres within federal protected areas and an additional 10 million hectares as Indigenous Lands (NPCC, 2008). The NAMA (Nationally Appropriate Mitigation Action) plan further advances these intensification goals through voluntary provisions focused on *Adaptation in Agriculture* including the restoration of grazing land, support of integrated crop-livestock systems and promotion of no-till farming (Embassy of the Federative Republic of Brazil, 2010). It is expected that combining these objectives with containment, supplemental feeding and integration with crop systems will improve efficiency and reduce the demand for newly cleared land (Galford et al., 2013). Finally, the national “Low-Carbon Agriculture” program provides approximately \$1.5 billion in annual subsidized loans to increase agricultural efficiency (Soares-Filho et al., 2014). These policies fully embrace the “Borlaug Hypothesis” or the presumption that intensifying agriculture can reduce development pressure on forests (Angelsen and Kaimowitz, 2001).

The impact of technical innovation on forest use and clearing remains a controversial issue (Marchand, 2012; Kaimowitz and Angelsen, 2008; Maertens et al., 2006). The historical increases in agricultural productivity associated with the Green Revolution were not without substantive environmental costs (Gollin et al., 2005). The multiplicity of the objectives (including the encouragement of agricultural productivity growth, improvements in rural livelihoods and the protection of environmental resources) were difficult to attain (Lee et al., 2006). Furthermore, market conditions can impact the efficacy of these policies over time. The “Boserup Hypothesis” (1965) suggests that intensification and extensification are positively correlated via resulting changes (from intensification) in food prices, technology, infrastructure, and population. Therefore, unless combined with forest preservation programs, increases in profitability, technological improvements and/or other developmental advances have the potential to attract new investment and reverse any initial reductions in forest pressure (Bowman et al., 2012).

While intensification practices have the potential to reduce expansion pressure in the Brazilian Amazon, two key issues complicate this outcome: (1) cattle extensification has played a historical role in the development of the Amazon (Walker et al., 2000; Faminow, 1998), and (2) the conversion of forest to pasture increases property value (Caviglia-Harris, 2005). The Brazilian cattle herd increased by more than 100% between 2000 and 2015, largely in response to an increasing role in global trade of beef (IBGE, 2017). Much of this increase has taken place within the states of the Legal Amazon: 75% of the national herd increase and 44% of the dairy herd increase occurred within these nine states (Fig. 1), and in particular in the “arc of deforestation,” (i.e. the states of Rondônia, Pará and Mato Grosso) where land use is largely characterized by pasture extensification and large-scale mechanized agriculture (Bowman et al., 2012). Cattle systems in this region vary from the more traditionally extensive rearing of cattle for slaughter, to cow/calf or “fattening” operations, and small-scale dairy farms that tend to lack efficiencies that would lead to more intensive production methods (Caviglia-Harris, 2005; Faminow, 1998; Margulis, 2004; Siegmund-Schultze et al., 2010). Extensive cattle system practices are the method of choice because they are cost effective, pasture is relatively cheap, and new land is perceived to be widely available. Although recent data suggest a strong trend towards intensification, levels of cattle intensification remain low compared to global averages (Dias et al., 2016). In addition to profits from production, the clearing of land for pasture increases property value. Land prices are actually 3 to 14 times higher once converted to pasture, reflecting the value added from the labor intensive clearing process (IPCIG, 2014).

Deforestation rates fell throughout the Amazon following the 2004 launch of the Plan to Prevent and Control Deforestation in the Brazilian Amazon (PPCD-AM) (Godar et al., 2014), but increased again after 2012. The deceleration of deforestation has made Brazil a global leader in climate change mitigation (Nepstad et al., 2014) and created momentum to enforce the 2012 Forest Code. However, the challenges of enforcing and maintaining effective policies are significant. Brazil has the largest and most advanced real-time deforestation monitoring system in the world (DETER, Detection of Deforestation in Real Time) and an extensive protected area network, which are both considered effective tools against deforestation (Walker et al., 2009; Nepstad et al., 2006). However, the cattle industry has a powerful lobby that played a key role in reducing the amount of land protected by the 2012 Forest Code (Cunha and Mello-Thery, 2010). It remains an open question as to the role that pasture management can play in meeting climate change goals.

At the same time, it is difficult for policy makers to ignore the potential for the adoption of intensification practices. First, proponents of these practices often claim they can theoretically increase agricultural productivity at little or no cost to environmental conservation. Second, the method has the potential for positive welfare effects. While small-scale farming accounts for only 25% of Brazilian agriculture, these operations hold over 80% of rural landholdings (Assunção et al., 2013). Increasing the productivity of the inefficient small-scale farmers has the potential to impact a large swath of the Brazilian Amazon, all while improving the income of a large share of relatively poor property owners. Lastly, recent research suggests increased use of intensification methods can indeed have positive impacts on the industry while reducing pressure on tropical forests (Martha et al., 2012; Millen et al., 2011), it is likely that policy makers see the support of these policies as a “no-brainer”.

This paper investigates the impact of intensification practices of small-scale farmers in the Brazilian Amazon on the demand for productive land (i.e. pasture) to determine if intensification policies can be expected to play a role in reducing pressure on marginal forests, and thus help to meet climate policy objectives. To begin, the theoretical underpinnings of the Borlaug and Boserup hypotheses are outlined with a simple agricultural production model that is then used to motivate the empirical models. A panel model of land use is estimated with data from small-scale farms that operate both as dairy farms and calving operations in the greater Ouro Preto do Oeste region of Rondônia, Brazil. Based on these results, the paper concludes that the reliance on policies that promote intensification may leave Brazil short of reaching its climate change objectives.

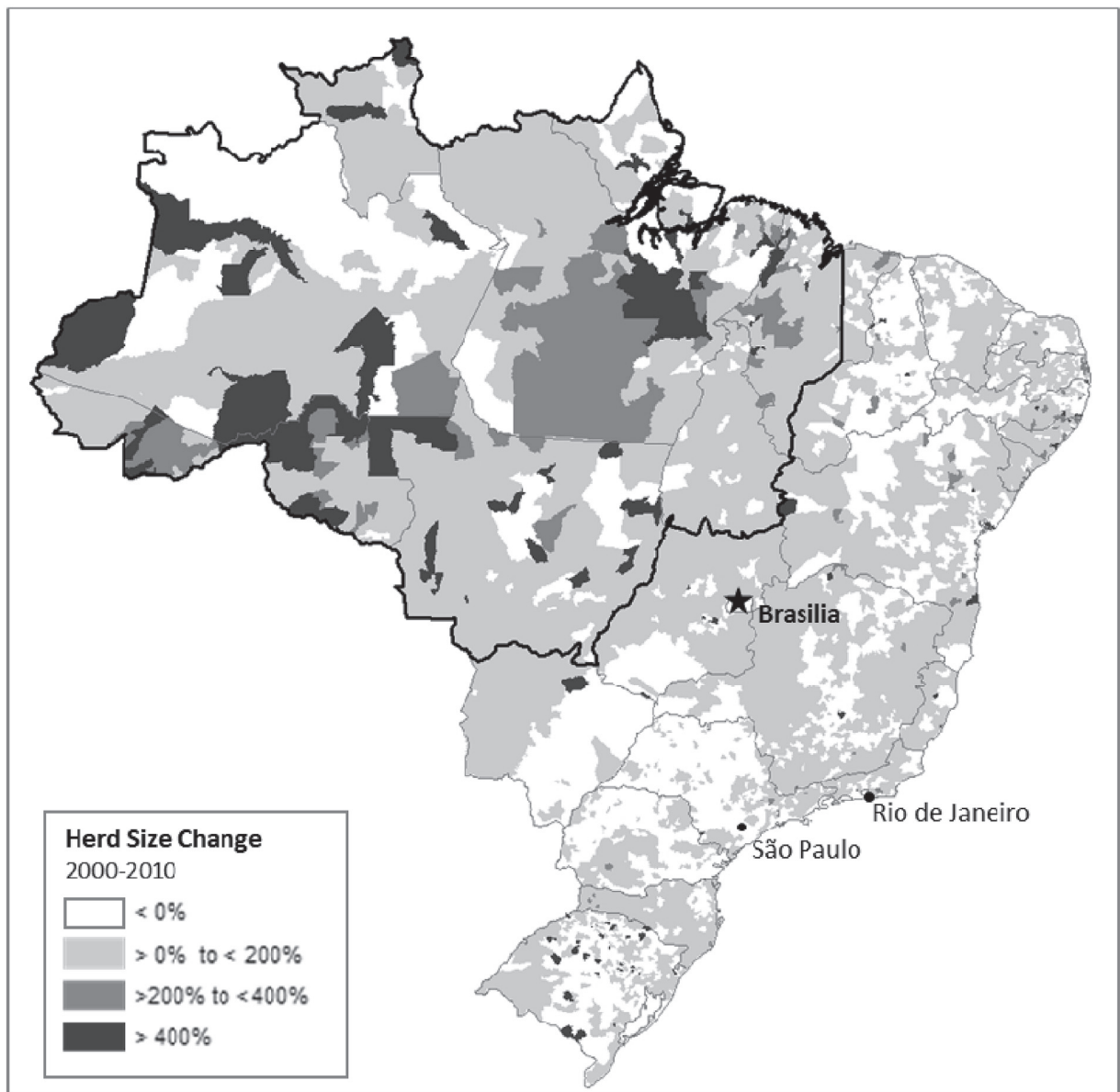


Fig. 1. Cattle herd changes by Municipality in Brazil, 2000–2010 (Brazil's Legal Amazon outlined in bold).

2. Conceptual framework

For illustrative purposes, the profit maximizing household is assumed to produce dairy (milk) and (instead of using the extensive practice of cutting forest to create pasture) to use prescribed burns (the technology, δ) on degraded pastures to create grasses (g) on land already in production as the means for intensification (although any input or group of inputs could be substituted). Pasture grasses can also be intensified with seed and fertilizer, although these methods are used less frequently due to cost. The degree of intensification is reflected by the amount of the input applied and/or the resulting output measures including milk per dairy cow and the beef income per unit of (beef) cattle. The choice of the degree of intensification is therefore the result of input choices and exogenous factors (e) that determine the rate at which inputs are converted into outputs including the biophysical characteristics of the lot (i.e. soil type, water availability and slope) and interactions of these characteristics with weather conditions. The input efficiency function, $h_i(\alpha)$ represents the portion of the input utilized by product j with technology i and land quality α .

In this example (where all time subscripts have been dropped for illustrative ease), it is assumed that households make choices to maximize profits from on-farm production of different agricultural goods. Production of each output can be represented by $Y_j = f(g_j, d_j)$ where g_j are the grasses available (improved with prescribed burns used to infuse nutrients), and d_j

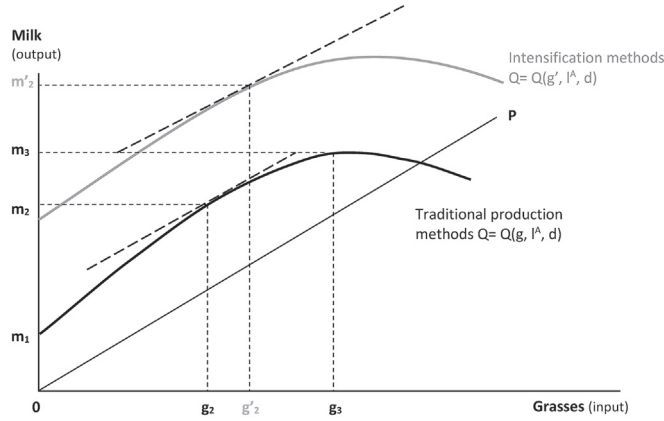


Fig. 2. Dairy (milk) output with fixed land assumption.

is the land in production allocated to produce output j . The total land in production for agriculture and livestock, $\sum_{j=1}^J d_j = d_i$ can never be greater than the amount of property owned ($\bar{D}$), although this limit can be increased with the purchase of additional property. Output is assumed to be twice differentiable and exhibit diminishing returns for the inputs. Thus, household agricultural profit can be written (without the household subscript)

$$Y = \sum_{j=1}^J [p_j q_j - p_g g_j - p_d d_j] \quad (1)$$

where q_j is the output of good j , p_j are the output prices, p_d is the price of land, and p_g is the price of grasses (represented by the price of seed, price of fertilizer or the labor input used for prescribed burns).

Following Caswell and Zilberman (1986), the optimization problem faced by the household for one output product, such as milk (m), when choosing the new technology, δ_i (i.e. intensification practices) can be written as:

$$\max_{\delta_i, d_j, g_j} \Pi = \delta_i(e)(f(h_i(\alpha), g_i, d_i) - p_d d_j - p_g g_j) \quad (2)$$

subject to $d_i \leq \bar{D}$, $\delta_i \in [0, 1]$. Here we have the classic solution where the marginal rate of substitution of grasses is equal to the price ratio. In other words, the farmer will employ grasses (and other inputs) at the margin such that the owner will receive the highest return for each input.

Profit maximization can also be represented graphically. A simplified one-factor production function shows the milk yield per cow (m) which would be expected for applying different amounts of grasses or fertile pasture (Timmer et al., 1983). This function (Fig. 2) assumes that land is fixed. If no fertilizer or prescribed burns are used to improve upon pasture ($\delta_i = 0$), an output of m_1 would be produced. The physical maximum yield per head of cow is m_3 which can only be accomplished with g_3 units of grasses. The production function therefore represents the rate at which grasses can be converted into liters of milk, or inversely, the rate at which farms can exchange milk for pasture. This tradeoff is reflected in the relative price of grasses to milk and is shown as line OP , where a change in relative prices would change the slope of this line. The maximum profit when using traditional non-intensified agricultural practices will occur at m_2 , where the distance between the output and input costs is the greatest. A technological change such as the use of more intensified practices alters the productivity of one or more inputs, here the productivity of grasses. This technological change shifts production function upward. The use of intensification strategies (when $\delta_i = 1$) illustrated through the use of a new seeds, fertilizer or burns applied to create higher quality or greener pastures, shifts the production function upward providing the opportunity to produce more output at all levels of grasses and a greater level of output (m'_2) at profit maximization.

Under scenarios in which the property size is fixed (and $\bar{D}$ does not change) the adoption of intensification practices can serve to reduce pressure on tropical forests through profit maximization: the practices are adopted when the costs of adoption are outweighed by the received gains. Intensification efforts make it possible for profits to be sustainable over time, eliminating the need for households to seek additional forest to clear for pasture (and increase the area in production, d_i). However, once the assumption of fixed land holdings is relaxed, the justification for support of intensification practices breaks down (Fig. 3). Where intensification practices lead to the more efficient use of an input, extensification is interpreted as the increased use of an input. When land in production can be varied, extensification practices can be profitable. Here the production function continues to be subject to diminishing returns (because land is not limitless) but extensification extends the peak production further along the input-axis. Depending upon the degree to which land can be expanded (d_1 or d_2), profit maximization could be greater or less than comparable change in intensification practices (Kaimowitz and Angelsen, 2008; Alvarez et al., 2008). For example, assuming the same relative prices for milk and grasses, if d_1 expansion opportunities are available, profit maximum occurs at m_3 , a

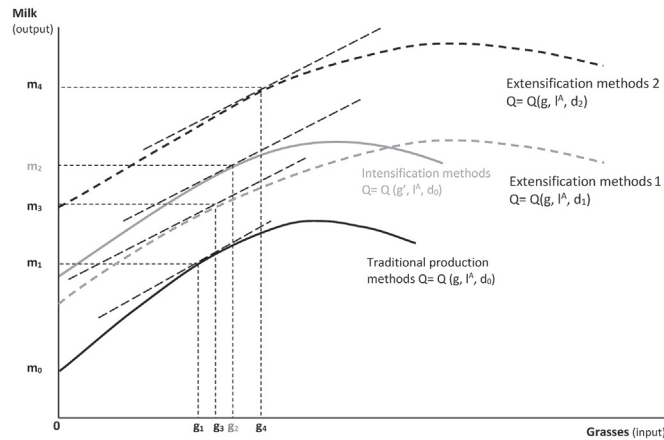


Fig. 3. Dairy (milk) output with fixed land assumption relaxed and expansion of extensification methods possible.

level of production that is lower and less profitable as compared to intensification. Similarly, if d_2 expansion opportunities are available, the profit maximum occurs at m_4 , a level of production that is higher and more profitable as compared to intensification. The only difference between the land expansion scenarios (d_1 and d_2) is the relative availability and price of land. Scenario 2 assumes a greater availability of marginal land available and therefore a lower price of land. In other words, holding other factors constant, the assumption that land available for future pasture use is fixed, results in conclusions that are consistent with the Borlaug Hypothesis, while relaxing this assumption results in a more complicated relationship between intensification and extensification predicted by Boserup. Therefore, even when holding factors that make extensification more likely constant (such as advances in development, expansions in infrastructure and changes in other relative prices), this simple model reveals that policies that support intensification as a means to reduce pressure on forest margins lie on shaky theoretical grounds. Under the right conditions, intensification can achieve these environmental goals (Alvarez et al., 2008), however these conditions are not guaranteed.

Returning to the optimization problem, if the assumption of fixed land is dropped, the household faces the following optimization when choosing the technology:

$$\max_{\delta_i, g_i, d_i} \Pi = \delta_i(e)[f(h_i(\alpha)g_i, d_i) - p_g g_i - p_d d_i - k_i] \quad (3)$$

$$s.t. \quad \bar{D} = d_i + d_0$$

where i is the application technology indicator, e is the effective input per hectare (or the exogenous influence on intensification), g_i is the applied input per hectare, d_i is deforested land, d_0 is the forested land not yet converted for agriculture α is land quality ($0 < \alpha < 1$), k_i is the cost of switching to the new technology, and $y = f(g, d)$ is the production function, where $f' > 0$ and $f'' < 0$.

Using a Cobb-Douglas production function, the household considers the alternative technology where β and γ are household preferences for grasses and land, respectively (and $\beta + \gamma = 1$).

$$\max_{\delta_i, g_i, d_i, \lambda} \mathcal{L} = \delta_i(e)[f(h_i(\alpha)g_i^\beta, d_i^\gamma) - p_g g_i - p_d d_i - k_i + \lambda \delta_i(\bar{D} - d_i - d_0)] \quad (4)$$

Once the optimal quantity of input to be used under each technology is identified, the discrete choice problem is solved by choosing the technology that maximizes profit. The marginal rates of substitution are:

$$\begin{aligned} MP_g &= \delta_i(\beta g_i^{1-\beta} d_i^\gamma) - p_g \\ MP_d &= \delta_i(g_i^\beta \gamma d_i^{1-\gamma}) - p_d - \lambda \delta_i \end{aligned} \quad (5)$$

Thus, the marginal rate of substitution of grasses for land is equal to the price ratio minus the price of land if intensification practices are chosen. In other words, the input tradeoff leads to a decrease in the marginal productivity of the adjusted input, while increasing the marginal productivity of the other. For example, an increase in fertilizer (or prescribed burns) could increase the marginal productivity of grasses if land quality is relatively poor, however this may not be the case for high quality soils, creating an increase in the demand for additional productive land. Thus, the derived demand for the input pasture, g_i is a function of all exogenous factors:

$$g_i^* = g^*(p_g, p_d, e, \beta, \gamma) \quad (6)$$

Therefore, and unsurprisingly, at the margin the farmer will improve upon grasses such that the household will receive the highest return for each input. More interestingly, the highest return depends on the sign of $\delta(g_i)/\delta(e)$ and the trade off between

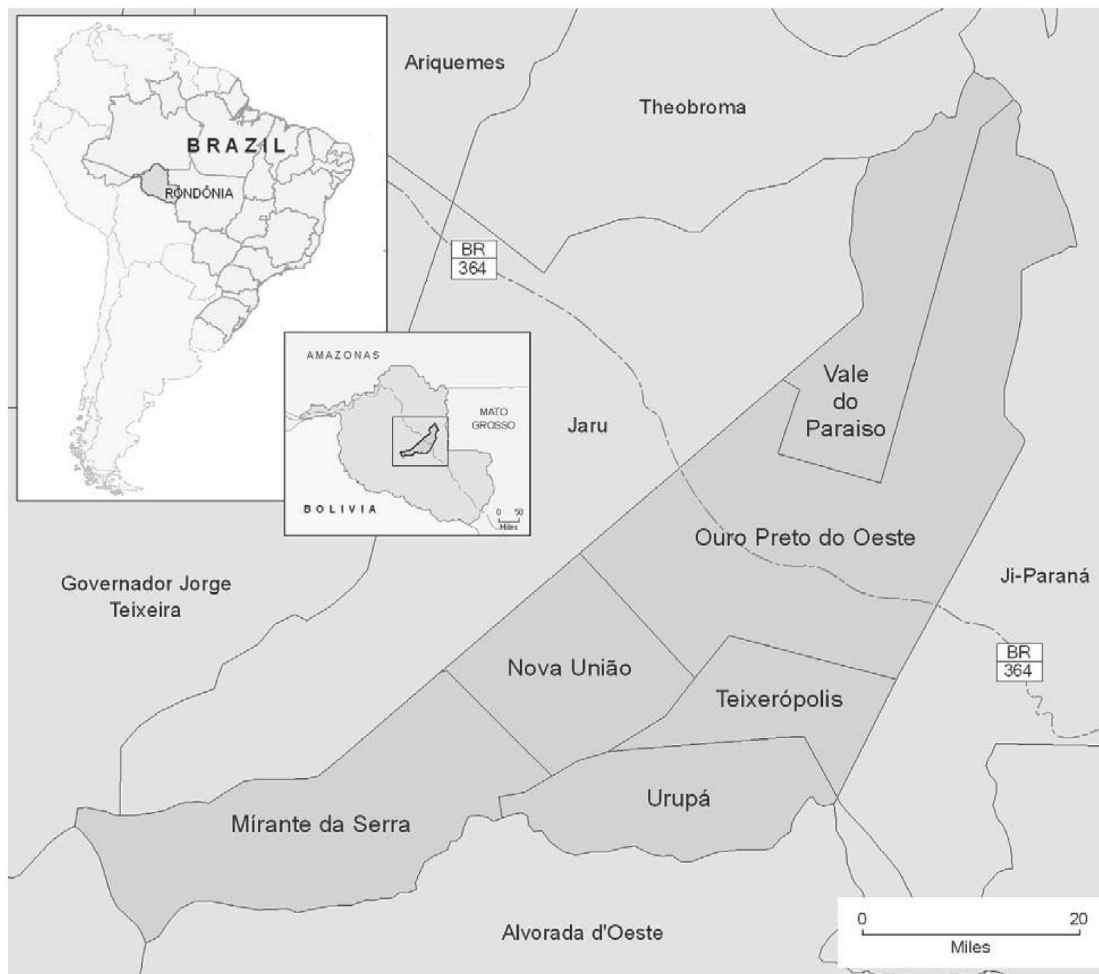


Fig. 4. Study Region, Ouro Preto do Oeste, Rondonia.

clearing or obtaining new land and the application of fertilizer, seeds or burns to improve the extent and quality of grasses. The sign will depend on the elasticity of input use efficiency and relative soil quality.

The demand for grasses may also be a function of e through several different pathways not represented in this simplified model. First, e may serve as a substitute or complement for household labor, depending on the degree of intensification/extensification. Second, there may be complementarities among production activities such as the production of dairy, beef and calves, which enable greater production of all output types per unit of land. Finally, the use of different production activities, which do not require cattle and are therefore land intensive (such as fish, non-timber forest products and crops), may reduce the household demand for additional grasses.

The key implications of this conceptual framework are that the derived demand for pasture grasses operates via the biophysical properties of the land, market prices and household preferences. Intensification practices influence the rate at which inputs are transferred into outputs and, thus, operate via these exogenous characteristics (e). The following sections summarize available data, mapping the measurement of these different influences to the categories outlined in the conceptual framework and outline the empirical approach, which applies this framework to panel estimations.

3. Study region and data

The data employed in the empirical analysis were collected as part of a longitudinal study focused on identifying the trade-offs between development and deforestation in a region officially settled in 1970 as part of Brazil's agrarian reform program implemented by the National Institute of Colonization and Agrarian Reform (INCRA). The state of Rondonia has experienced some of the highest rates of deforestation in the Brazilian Amazon, placing it within what is known as the "arc of deforestation" (Aldrich et al., 2006). The study region is comprised of the six municipalities that make up Greater Ouro Preto do Oeste, Rondonia, located in the approximate center of the state and considered a 'post' frontier region settled over 40 years ago (Fig. 4).

Similar to the hundreds of other settlements established in the 1970s, INCRA awarded titles to 100 ha (and later 50) parcels along rectangular grids in the six municipalities without consideration for topography, hydrology, soil type or other environmental constraints (Millikan, 1992). The municipalities in Ouro Preto do Oeste are similar to other municipalities with INCRA settlements as measured by average monthly income, GDP per capita, and the Human Development Index (a composite index of life expectancy, education, and income) (IBGE, 2015; PNUD, 2013). However, there are notable regional differences in terms of the sources of income and welfare (Bell et al., 2013). While Rondônia holds a comparative advantage in dairy, other states within the heavily deforested arc of deforestation have different production advantages. These include, Pará, which has a greater focus on perennial crops including (but not limited to) cassava, peppercorn and sugarcane (Siegmund-Schultze et al., 2010); Mato Grosso, which has a focus on large-scale mechanized soy and ranching operations (VanWey et al., 2007); Acre (although noted as the “greenest” state in the Amazon), which is focused on rubber tapping and sustainable forestry, but is slowly expanding ranching operations (Hoelle, 2014); and Maranhão, which has a weaker agricultural sector but is industrializing (Miranda, 2012).

Despite these differences, trends in the cattle herd and related industries have been increasing at relatively rapid rates in the study region and throughout the Amazon since 1991 (Table 1). For example, the cattle herd increased by more than 50% in each decade since 1991 for the study region, for the state of Rondônia and for municipalities with INCRA settlements established prior to 2000. This increase was almost 200% for the study region between 1991 and 2000, but in the next decade, the rate of growth was greater throughout the Amazon and state of Rondônia. Cattle per hectare of deforestation (or cleared forest) and dairy head per hectare decline over time for each of these regions, suggesting a movement toward more extensive practices (although likely overestimated since pasture productivity declines over time, and therefore not all cleared land can support cattle). The cattle herd increased at significantly higher rates while milk production rates (per head) was higher in the study region in each of these decades. While efficiency gains can be noted in the milk production over time, these levels remain 50% lower than the more fertile south and southeastern regions of the nation (IBGE, 2012a; IBGE, 2012b). In sum, census data suggest an increasing role for cattle and related industries throughout the Amazon, but a greater concentration of dairy in the study region and state of Rondônia. Farmers in the study region therefore have a greater intensification choice set that applies to the production of beef cattle, dairy cattle and milk as compared to other municipalities throughout the Amazon.

Household survey data consist of 938 observations from a stratified random sample designed to be representative of the rural population in each of the six municipalities in Greater Ouro Preto do Oeste. The survey was administered in 4 waves: 1996, 2000, 2005, and 2009. All households interviewed in 1996 were returned to in following years (Caviglia, 1999; Caviglia-Harris et al., 2013). The sample size was expanded in 2005 and again in 2009 to include new settlements established in the study region on previous forest reserves or large ranches; compensate for attrition occurring between waves; and maintain a representative sample population within the original and newly settled areas (Caviglia-Harris et al., 2012). The survey data include demographic characteristics of the household, hectares of land in different land uses, farm production (including milk, annual and perennial crops and livestock goods); total income of the household (including off-farm employment, and government payments); and assets owned by the household (such as vehicles, equipment and consumer durables). These observations are combined with geospatial data including classified land cover data (Roberts et al., 2002), property location and bio-physical characteristics of the farm lot (i.e. soil, slope, elevation and distance to the city center). All households hold legal and fully recognized property rights (Caviglia-Harris et al., 2015).

The Ouro Preto do Oeste region has seen a decline in mature forest from an average of 30 percent of the owned land in 1996 to 12 percent in 2009. The typical land use trajectory has been the conversion of forest to first harvest annual crops, followed by perennial crops, and later pasture primarily for dairy cattle. This pattern is consistent with the household ‘lifecycle’ model (Perz and Walker, 2002; VanWey et al., 2007) that has been widely posited to explain land use change in the Amazon (Walker et al., 2000; Barbieri et al., 2006; Siegmund-Schultze et al., 2010). According to this pattern, households first harvest and sell annual crops since the investment is relatively low (i.e. they need only purchase or acquire seed), then later, once they have the ability to purchase or acquire perennials, they harvest and sell these crops. They lastly invest in cattle which serve as insurance and a source of dairy, beef and calves. However, this sequence has been changing as new arrivals enter the dairy, calf, and beef markets more quickly (Hall and Caviglia-Harris, 2013). By 2009, over three quarters of the average lot in the study area was in pasture, and income from milk production and sales had risen from 25 to 33% of total annual household income. In addition to growth in the volume of milk production, revenues also increased due to investment in refrigerated tanks that allow households to obtain better prices for higher quality milk. The milk market is relatively advanced. There are a large number of producers (81% of households sell milk) who can choose between 2 and 6 different milk processing plants, which provide farm-gate pick up once per day every day of the year. Evidence suggests competitive pricing exists as there are a large number of buyers and sellers and little within season variation in prices. Farmers milk the cows in the morning, place the harvested milk in an airtight and sunlight impervious container located roadside and leave at the front of the property for pickup. The raw milk can remain at the roadside for 30 min to 6 h depending upon the location of the property on the collection route. Given exposure to heat, the raw milk is not processed for drinking but rather pasteurized and used in cheese production. The beef market continues to advance, but is less developed in comparison to the milk market because households often do not have the financial capital required to purchase large numbers of cattle or the feed necessary to fatten the herd for sale as beef. Instead, the irregular sale of beef at farmers’ markets and the sale of calves to a few more recently established large ranches occurs.

Table 1

Cattle and dairy trends in study region, Rondônia, and comparable Amazonian municipalities; 1991–2010.

	Cattle (head)	Dairy (head)	Milk (thousands of liters/year)	Cattle (per hectare ^d)	Dairy (per hectare ^d)	Milk (liters/ cow/day)	Percent Change ^e Cattle	Percent Change Dairy	Percent Change Milk	Percent Change Cattle/ha	Percent Change Dairy/ha	Percent Change Milk/day
1991												
Ouro Preto do Oeste ^a	197,914	39,582	24,937	5.35	1.07	1.73	NA	NA	NA	NA	NA	NA
Rondonia ^b	2,367,625	358,648	204,685	4.18	0.62	1.56	NA	NA	NA	NA	NA	NA
Amazon ^c	16,670,089	1,369,308	542,165	4.78	0.35	1.26	NA	NA	NA	NA	NA	NA
2000												
Ouro Preto do Oeste	574,553	74,167	88,900	1.26	0.15	3.23	190.30	87.38	256.50	−76.37	−86.06	87.03
Rondonia	3,728,392	277,496	238,493	0.80	0.06	2.46	57.47	−22.63	16.52	−80.76	−91.08	57.56
Amazon	28,902,595	1,394,073	857,497	2.52	0.13	1.74	73.38	1.81	58.16	−47.34	−63.49	38.13
2010												
Ouro Preto do Oeste	879,553	204,310	172,036	1.90	0.44	2.30	53.08	175.47	93.52	49.98	198.14	−28.81
Rondonia	8,402,948	649,473	469,568	1.39	0.12	1.73	125.38	134.05	96.89	73.23	110.01	−29.75
Amazon	48,335,661	1,872,260	1,489,393	2.24	0.10	2.15	67.24	34.30	73.69	−11.15	−23.03	23.64

^a Greater Ouro Preto do Oeste includes the six municipalities of Mirante da Serra, Nova União, Ouro Preto do Oeste, Teixeropolis, Urupá, and Vale do Pará.^b Includes all municipalities within the state settled prior to 2000 with the exception of the 6 municipalities in Greater Ouro Preto do Oeste.^c Calculated as the total per municipality for all municipalities with INCRA settlement established prior to 2000.^d Per hectare of deforestation.^e Percent changes represent decade changes between each census year beginning in 1991; the first percent change therefore represents the change from 1991 to 2000, etc.Sources: IBGE - Pesquisa Pecuária Municipal "Tabela 73 - Efetivo dos rebanhos, por tipo de rebanho (série encerrada), <http://www.sidra.ibge.gov.br/bda/acervo/> accessed January 2016. (Number of head includes cows, calves and bulls); INPE. 2011. "Projeto Prodes: Monitoramento Da Floresta Amazônica Brasileira Por Satélite." Guamá Belém (PA) Brasil: National Institute for Space Research (INPE). http://www.obt.inpe.br/prodes/sisprodes2000_2010.htm.

Table 2

Descriptive Statistics by Year, mean and standard deviation (in parentheses).

	Definition	1996	2000	2005	2009
Land in Production (pasture grasses)	Hectares of pasture on the property, calculated from remote sensing data	46.45 (24.60)	57.75 (25.96)	53.68 (32.89)	53.18 (41.15)
Percentage in Production	Percentage of property in pasture	59.47 (18.77)	72.41 (17.16)	75.90 (19.52)	80.34 (17.11)
Beef Intensification	Beef income per cattle head, R\$2000	0.00 (0.00)	60.18 (114.1)	98.02 (199.7)	155.8 (561.9)
Dairy Intensification	Liters of milk produced per dairy head per day	3.372 (3.064)	4.172 (1.640)	3.444 (2.383)	4.824 (3.832)
Cattle Intensification	Cattle per hectare of pasture	1.766 (2.650)	1.819 (1.224)	2.665 (2.398)	2.437 (1.872)
Corral	Ownership of a corral with cement flooring; = 1 if owned, 0 otherwise	0.00 (0.00)	0.00 (0.00)	0.193 (0.408)	0.226 (0.419)
Soil	Soil type; ability to support agriculture (1-good, 2-moderate, 3-restricted, 4-unsuitable)	2.221 (0.775)	2.137 (0.763)	2.267 (0.776)	2.337 (0.742)
Slope	Average slope gradient on the lot, percent	5.373 (3.732)	5.025 (2.673)	5.517 (3.363)	5.295 (3.471)
Elevation	Average elevation on the lot derived from STRM 3 arc second (90 m)	230.8 (44.67)	226.0 (40.89)	234.3 (43.64)	227.8 (43.23)
Distance	Distance to the urban center and markets, kilometers	36.41 (17.65)	36.33 (17.71)	38.46 (18.09)	39.90 (17.19)
Lot size	Hectares	73.56 (47.93)	65.50 (34.38)	61.40 (48.67)	53.53 (46.70)
Obs.		171	138	213	416

The average amount of land in pasture increased from 46 ha in 1996 to 53 by 2009 (Table 2). This increase is greater than the change in the percent of the property in production (which increased from 60 to 80%) because portions of properties were sold in some cases, and because new residents received or purchased smaller lots than the 100 ha distributed in the early settlement period. The average lot decreased in size from 74 to 54 ha by 2009. Soil type is classified as moderate in terms of its ability to support agriculture, reflecting relatively good soil conditions for the Amazon (Numata et al., 2007) and a relatively low average slope gradient of 5%. Average pasture size increased over time at a declining rate; from 1996–2000, 2.5 new hectares were added on average; from 2000–2005, 1.3 new hectares were added; and from 2005–2009, 0.35 new hectares were added (Table 2). The average property is approximately 40 km from the main urban center.

Beef and milk production require—at a minimum—grasses (i.e. productive pasture) and a water source. Households use prescribed burns, fertilizer and herbicides to increase pasture; purchase cattle feed to augment grass production; and provide salt and other minerals to support nutrition. Purchased inputs are used by few households due to income constraints (e.g. only 1% of households applied fertilizer in 2009). The use of intensification practices that can be implemented with little cost (such as walking cattle to shade and water, creating ponds for water, or damming streams) can also be measured by the impact on output, here income from the beef and calf trade per head of the herd and the milk produced per dairy cow (for participation in the dairy trade). Because households can choose to intensify along more than one production system, the degree of intensification is not additive across output markets. For example, households can intensify by only undertaking practices which increase dairy production (because they do not participate in the beef or calf markets), households could choose to intensify beef or calf production, or households could adopt methods that intensify output in both of these related markets. However, there is little overlap in these markets since households most often choose to produce milk or beef. No more than 9% of the sample households intensively produces in both markets in any year. In 1996 no households that specialized in milk production sold calves or beef. In 2000, 1% of households specialize in both markets, while in 2005 this is 1% and in 2009 this is 2%. Beef harvest and the calf trade intensified over the study period from no recorded trades in 1996 (i.e. no households in the sample sold calves or beef) to an average of R\$156 per head of cattle while milk production intensified from 3 L per head per day to almost 5, with a dip in 2005 likely due to an extensive drought (Table 2). Here beef income per head represents the ratio of the beef and calf sales relative to the total herd. Since households can sell cuts to butchers and trade calves (and cattle) by the head, this measurement (calculated in real R\$) captures the relative degree of market participation (i.e. total sales per head of cattle). The cattle stocking rate (correlated with the dependent variable and therefore not used in the estimations to follow) also increased over the study period, from an average of 1.8 head per hectare in 1996 to over 2.4 by 2009. These values are higher than those calculated from census data (Table 1) and suggest higher efficiencies as compared to the remainder of the Amazon.

4. Results

The Borlaug and Boserup hypotheses imply that intensification practices impact the desire to expand operations which in turn impact the demand for productive land in a linear and non-linear way, respectively. The goal of these estimations is to discriminate between these two hypotheses because they have different implications for extensification and therefore policy

Table 3

Estimation of productive land (dependent variable: Pasture in hectares).

	Borlaug			Boserup		
	OLS (1)	Fixed (2)	Random (3)	OLS (4)	Fixed (5)	Random (6)
Constant	47.562*** (6.085)	−2725.02*** (973.879)	44.690*** (7.965)	47.006*** (6.254)	−2609.92*** (972.320)	45.261*** (8.023)
Beef income per head	0.009 (0.005)	0.005* (0.004)	0.007* (0.004)	0.039*** (0.013)	0.035** (0.014)	0.036*** (0.011)
Beef income per head ²				−0.000** (0.000)	−0.000** (0.000)	−0.000*** (0.000)
Milk per head	−0.544* (0.299)	−0.381* (0.195)	−0.464** (0.196)	−0.393 (0.658)	−0.270 (0.544)	−0.647 (0.495)
Milk per head ²				−0.001 (0.020)	0.000 (0.015)	0.009 (0.014)
Corral	6.448** (2.657)	5.573** (2.593)	6.648*** (2.212)	6.038** (2.654)	5.858** (2.588)	6.691*** (2.204)
Soil	−3.112** (1.338)	−313.191*** (71.185)	−3.000 (1.858)	−3.218** (1.335)	−315.971*** (70.882)	−3.062* (1.853)
Slope	−0.801*** (0.298)	21.705 (14.015)	−0.740* (0.397)	−0.801*** (0.297)	23.722* (13.982)	−0.726* (0.396)
Elevation	−0.003 (0.022)	9.457*** (2.327)	0.02 (0.031)	−0.003 (0.022)	9.028*** (2.324)	0.019 (0.030)
Distance to city center	−0.458*** (0.056)	30.855 (19.800)	−0.478*** (0.075)	−0.451*** (0.056)	30.297 (19.754)	−0.473*** (0.075)
Lot size, hectares	0.399*** (0.020)	0.104*** (0.029)	0.312*** (0.020)	0.400*** (0.020)	0.102*** (0.028)	0.311*** (0.020)
Year 2000-dummy	14.148*** (3.032)	9.986*** (1.630)	12.689*** (1.669)	13.310*** (3.068)	9.151*** (1.727)	12.163*** (1.725)
Year 2005-dummy	11.689*** (2.777)	13.978*** (1.730)	15.025*** (1.711)	10.702*** (2.793)	12.848*** (1.790)	13.974*** (1.739)
Year 2009-dummy	15.396*** (2.554)	15.816*** (1.829)	17.708*** (1.732)	13.989*** (2.630)	14.341*** (1.956)	16.525*** (1.806)
R-squared	0.43	0.36		0.44	0.37	
F-test		6.67***			6.68***	
Hausman			95.89***			114.55***
Number of panels		549	549		549	549
Obs.	938	938	938	938	938	938

Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%.

designed to promote intensification. The empirical approach used to represent this relationship is outlined in Equation (7) where intensification is included as a determinant of the demand for productive grasses:

$$g_{it} = \alpha_i + \beta_1 I_{it} + \beta_2 X_{it} + \beta_3 H_{it} + \mu_i + \epsilon_{it} \quad (7)$$

Here the pasture of household i in time period t is a function of intensification practices (I) measured by milk production per cow and beef/calves sales per herd, property characteristics (X) including soil, slope, elevation, distance from the city center and property size and household infrastructure (H) including a cement corral. This equation is estimated with fixed and random effects, where the fixed effects model includes within-household variation and the error μ_i and the random effects includes this plus the between-household variation and the error ϵ_{it} .

The conceptual framework highlights several issues that need to be accounted for in the estimations. First, changes in demand occur both within households and over time. It is therefore possible that unobserved differences and changes over time impact the demand that would not be accounted for in an ordinary least squares (OLS) regression. For example, intensification increases and changes in demand can be driven by exogenous shocks (such as droughts or economic crises) that would bias the estimated impact of intensification. Panel models (i.e. fixed and random effects) are estimated to reduce the likelihood of omitted variable bias and control for year effects (i.e. aggregate time-series changes). OLS estimation results (including year dummies to control for time effects) are presented for comparison. An F-test of the joint significance of the fixed effects intercepts is used to determine if a panel model is empirically supported, while a Hausman test is used to test the fixed and random effects assumptions.

To study the relationship between intensification and pasture one would ideally have information on the direct factors that influence intensification choices including cow age, genetics, and animal health, and others related to climate such as rainfall and temperature. Unfortunately, detailed information on the cattle herd makeup was not included in the household survey and is not available for use in this analysis. As long as these factors are fixed over time (i.e. the farmer does not adopt a different herd ratio to respond to policy incentives to increase intensification or reduce pasture expansion) no bias would be introduced into the panel analysis. This is likely true across households for climate since all farmers experience the same rainfall and temperature, but may not hold between and across households over time for the herd makeup. If it is assumed that herd adaptations would be

Table 4

Estimation of productive land (dependent variable: Percentage of pasture).

	Borlaug			Boserup		
	OLS (1)	Fixed (2)	Random (3)	OLS (4)	Fixed (5)	Random (6)
Constant	92.601*** (3.834)	187.302 (688.211)	87.403*** (4.669)	89.478*** (3.928)	149.271 (689.392)	85.563*** (4.699)
Beef income per head	0.001 (0.003)	0.004 (0.003)	0.003 (0.003)	0.009 (0.008)	0.010 (0.010)	0.011* (0.007)
Beef income per head ²				0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
Milk per head	−0.392** (0.188)	−0.339** (0.138)	−0.318** (0.128)	0.794* (0.413)	0.245 (0.385)	0.428 (0.319)
Milk per head ²				−0.039*** (0.013)	−0.017 (0.011)	−0.022** (0.009)
Corral	2.556 (1.674)	−3.418* (1.832)	−0.61 (1.403)	2.293 (1.667)	−3.522* (1.835)	−0.736 (1.401)
Soil	−3.693*** (0.843)	−72.392 (50.305)	−3.294*** (1.083)	−3.699*** (0.839)	−73.503 (50.257)	−3.355*** (1.076)
Slope	−1.518*** (0.188)	11.708 (9.904)	−1.652*** (0.232)	−1.517*** (0.187)	12.393 (9.914)	−1.643*** (0.231)
Elevation	−0.026* (0.014)	−1.294 (1.644)	−0.013 (0.018)	−0.027** (0.014)	−1.359 (1.648)	−0.014 (0.018)
Distance to city center	−0.179*** (0.035)	7.065 (13.992)	−0.164*** (0.044)	−0.180*** (0.035)	8.372 (14.006)	−0.165*** (0.044)
Lot size, hectares	−0.039*** (0.012)	0.022 (0.020)	−0.009 (0.012)	−0.036*** (0.012)	0.021 (0.020)	−0.009 (0.012)
Year 2000-dummy	11.941*** (1.910)	12.927*** (1.152)	12.379*** (1.105)	10.776*** (1.927)	12.249*** (1.224)	11.515*** (1.143)
Year 2005-dummy	16.359*** (1.750)	18.290*** (1.222)	17.262*** (1.122)	15.936*** (1.755)	18.070*** (1.269)	16.906*** (1.143)
Year 2009-dummy	20.896*** (1.609)	20.737*** (1.292)	20.417*** (1.126)	19.514*** (1.652)	20.097*** (1.387)	19.507*** (1.174)
R-squared	0.28	0.48		0.29	0.48	
F-test		5.19***			5.09***	
Hausman			18.01***			18.05**
Number of panels		549	549		549	549
Obs.	938	938	938	938	938	938

Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%.

used to increase intensification (and increase profits) this would be captured by the intensification proxy, but could potentially introduce bias to the estimators if correlated with one or more latent factors.

Two different measurements of pasture land are estimated: (1) the total amount of pasture on the property, and (2) the percentage of pasture on the property. The dependent variable is as a function of the exogenous and latent factors that determine the rate at which inputs are translated into outputs (and are proxied by the output of milk per cow and the sales from cattle per head). Two functional forms are estimated for each dependent variable. The first, titled “Borlaug”, is used to test the linear relationship between intensification and the demand for productive land (as the Borlaug hypothesis assumes this is negative and significant). The second, titled “Boserup”, is used to test the possibility of a non-linear (and positive) impact on the demand

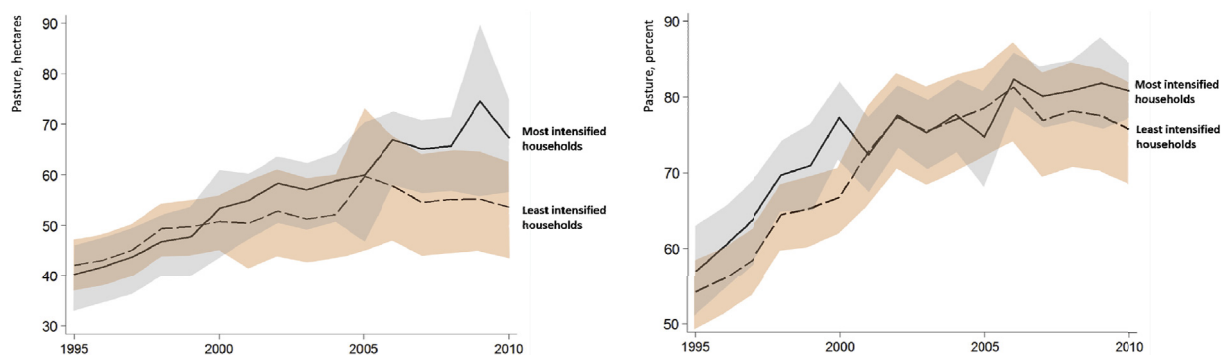


Fig. 5. Pasture and percent pasture for the most and least intensified cattle producers over time, remote sensing data (1995–2010). (confidence intervals shaded in gray for most intensified, orange for least intensified). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

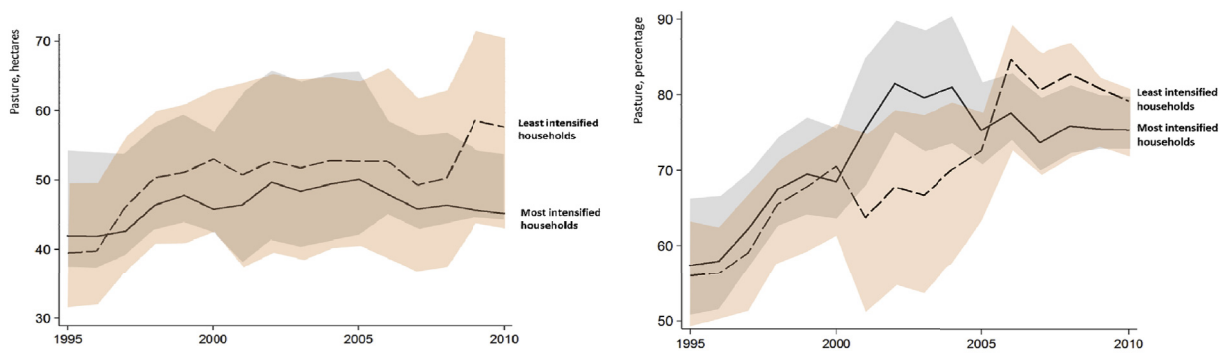


Fig. 6. Pasture and percent pasture for the most and least intensified dairy producers over time, remote sensing data (1995–2010). (confidence intervals shaded in gray for most intensified, orange for least intensified). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

for productive land (as the Boserup hypothesis assumes this relationship could be negative, positive or non-linear).

Table 3 includes the results of the estimation of the total amount of productive land on the property. Models 1–3 examine the linear relationship between intensification and the demand for productive land. An F-test rejects equal fixed effects across units ($F = 6.67$), meaning that fixed effects are non-zero and the pooled OLS is biased. Furthermore, a Hausman test ($\chi^2 = 95.89$) suggests that the random effects estimates are inconsistent, and therefore the less efficient, but consistent, fixed effects model is supported. The fixed-effect results suggest that the greater the degree of cattle production intensification, the greater is the demand for productive land, but the opposite is true for the intensification of milk production. Also significant are the year dummy variables (the size and sign of which suggest that the demand for productive grasses has increased consistently over time), the initial soil conditions (suggesting that households with more productive soils demand less land for grasses), elevation (those households on lands with higher elevations demand more grasses), and distance to the city center (households located further from the city center demand more grasses). Models 4–6 test for non-linear relationship between intensification and the demand for productive land by adding a quadratic term for intensification.¹ The fixed effects results support the Boserup hypothesis for beef production, or that intensification first increases but then decreases the demand for productive land. However, there is no significant relationship identified for the intensification as measured by dairy production in this specification. Similar conclusions on the sign and significance of the remaining model covariates are the same as those found for models 1–3.

Table 4 includes the results of the estimation of the percentage of productive land on the property. Similar to the previous estimations, models 1–3 examine the linear relationship between intensification and the demand for productive land, while models 4–6 examine the non-linear relationship. The fixed-effect results suggest that the greater the degree of milk intensification the smaller is the demand for productive land, but there are no significant impacts noted for cattle intensification.² Also significant are the year dummy variables for years; the size and sign suggest that the demand for productive grasses (as a percentage of the property) has increased over time. Models 4–6 test for non-linear relationship between intensification and the demand for productive grasses.³ The fixed effects results do not support the Boserup hypothesis nor do they suggest a significant impact of intensification on the percentage of the property in pasture. Similar conclusions on the sign and significance of the remaining model covariates are found for models 1–3.

The combined results of these estimations are therefore mixed: the intensification of beef and dairy production encourage and discourage the amount of cleared land both in absolute and percentage terms. These relationships are complicated by the fact that households can be intensified in both, one or neither of these production choices. While the percentage of households to produce both outputs is relatively high in any survey year (increasing from 48% in 2000 to 76% by 2009) the number of households to intensify in both production types remained relatively low (increasing from 7% in 2000 to 10% by 2009) suggesting that households are choosing production specialization over diversification.

To shed light on these findings, the absolute and percentage of land cleared by the most intensified (those in the upper quartile) and the least intensified (those in the lower quartile) for beef and milk production are plotted for 1995–2010; filling in gaps before and after the survey years with remote sensing land cover data clipped for each surveyed property (Figs. 5 and 6). These graphs suggest that the most intensified calf and beef producers have a greater amount of pasture (in both absolute and percentage terms), particularly after 2005. In contrast, the most intensified dairy producers have a smaller amount of pasture (in both absolute and percentage terms) in many but not all years, with a noted divergence for the most and least intensified households after 2005. These results suggest a behavioral change occurred after 2005, a year in which there was an extensive

¹ An F-test rejects equal fixed effects across units ($F = 6.68$), meaning that fixed effects are non-zero and the pooled OLS is biased. Furthermore, a Hausman test ($\chi^2 = 114.55$) suggests that the random effects estimates are inconsistent, and therefore the less efficient, but consistent, fixed effects model is supported.

² An F-test of the joint significance suggests panel fixed effects ($F = 5.19$), while a Hausman test ($\chi^2 = 18.01$) supports the fixed effects over the random effects model.

³ An F-test rejects equal fixed effects across units ($F = 5.09$). Furthermore, a Hausman test ($\chi^2 = 18.05$) suggests that the random effects estimates are inconsistent, and therefore the less efficient.

Table 5
Estimation of productive land, extensification potential comparisons.

	Pasture, hectares				Pasture, percentage			
	Properties with >50% Deforestation in 1996 (n = 349)		Properties with <50% Deforestation in 1996 (n = 171)		Properties with >50% Deforestation in 1996 (n = 349)		Properties with <50% Deforestation in 1996 (n = 171)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Beef income per head	0.080*** (0.021)	−0.02 (0.044)	0.006 (0.019)	−0.02 (0.047)	−0.008 (0.031)	−0.008 (0.031)	0.02 (0.022)	0.033 (0.049)
Beef income per head		0.000* (0.000)		0.000 (0.000)		0.000 (0.000)		0.000 (0.000)
Milk per head	−0.292*** (0.332)	−0.363 (0.640)	−0.713*** (0.223)	−0.384 (0.784)	0.148 (0.448)	0.148 (0.448)	−0.731*** (0.254)	0.700 (0.827)
Milk per head ²		0.003 (0.018)		−0.009 (0.020)		−0.009 (0.013)		−0.041** (0.021)

Notes: Models include the same covariates as noted in Table 3. Fixed effects coefficients are noted. Similar to previous models and F-tests of the joint significance suggests panel effects, while Hausman tests ($\chi^2 > 68$) support the fixed effects models. Remote sensing data for 1996 (used to select the sample) was available for the 520 properties included here. Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%.

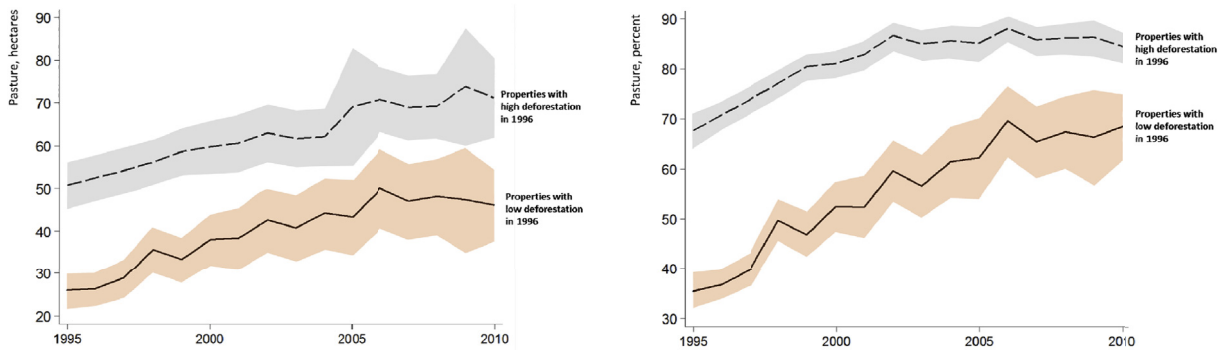


Fig. 7. Pasture and percent pasture for properties with high and low levels of deforestation in 1996, remote sensing data (1995–2010). (confidence intervals shaded in gray for high deforestation properties, orange for low deforestation properties). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

drought throughout the Amazon and including the study region (Lewis et al., 2011; Phillips et al., 2009). For example, the milk harvest declined by 33% in 2005 and motivated a ten-fold increase in the number of retention ponds recorded in Google Earth. In the context of intensification it appears that this drought may have triggered different responses from households intensified in beef production as compared to those most intensified in regards to dairy.

Deforestation is relatively high in the Ouro Preto do Oeste municipalities, with percentages of the property cleared increasing from 71% in 1996 to 90% in 2009 on average. Because land markets are thin due to sales that are hindered by INCRA and difficulties accessing credit (Vosti et al., 2001; Campari, 2005), it is likely that for households with limited ability to expand pasture, the turning point identified for cattle intensification is a reflection of this limit. Lot size is controlled for in the regressions, but is allowed to marginally vary over time (as households buy and sell portions of their properties). However, land market developments that increase the volume of trading may result in changes beyond the scope of these models. To address this concern, the models are estimated with data divided between households with more than 50% of the property in pasture in 1996 (and 24 ha available for future use as pasture) and those with less than 50% (the approximate median) of the property in pasture in 1996 (and more than 47 ha available for future use as pasture). This reduces the sample to those lots for which land cover and survey data are available in most survey years to create an unbalanced panel of ($n = 520$). According to the results noted in Table 5, the “Boserup” models do not suggest that intensification impacts the demand for productive land, however the “Borlaug” models suggest that dairy intensification reduces the demand for productive land while cattle intensification increases the demand for cleared land for those households with less than 50% of the property cleared in 1996.

To draw further conclusions on this property division, the absolute and percentage of land used as pasture by households with more and less than 50% of the property cleared in 1996 are plotted for 1995–2010; filling in gaps before and after the survey years with remote sensing land cover data clipped for each surveyed property (Fig. 7). These graphs suggest that the history of land clearing matters. Those households with more than 50% of the property deforested in 1996 have significantly higher levels of pasture (and percentages in pasture) in all years. Furthermore, the same estimations are made for large and small properties, as defined by the median property size (Table 6). These estimations of the percent of the property that is converted to pasture are more random in nature (i.e. the random effects models are supported for the percent pasture estimations) suggesting that there may be heterogeneous effects by property size: milk production reduces pressure on pasture expansion for landowners with

Table 6
Estimation of productive land, property size comparisons.

	Pasture, hectares				Pasture, percentage			
	Properties <50 ha ($n = 444$)		Properties >50 ha ($n = 494$)		Properties <50 ha ($n = 444$)		Properties >50 ha ($n = 494$)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Beef income per head	0.001 (0.003)	0.019* (0.011)	0.016 (0.017)	−0.047 (0.038)	−0.001 (0.004)	0.005 (0.009)	0.011 (0.010)	−0.008 (0.017)
Beef income per head		0.000 (0.000)		0.000* (0.000)		0.000 (0.000)		0.000 (0.000)
Milk per head	−0.052 (0.280)	−0.235 (0.714)	−0.421** (0.162)	−0.186 (0.596)	−0.013 (0.294)	0.693 (0.770)	−0.367*** (0.139)	0.378 (0.472)
Milk per head ²		0.029 (0.049)		−0.007 (0.015)		−0.045 (0.053)		−0.020* (0.012)

Notes: Models include the same covariates as noted in Table 3. Fixed and random effects coefficients are noted. Similar to previous models and F-tests of the joint significance suggests panel effects, while Hausman tests support the fixed effects models for the pasture estimations and random effects models for the percentage estimations. Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%.

larger properties, however this could be potentially offset by the weak (but reverse effect) of cattle intensification on pasture expansion.

5. Conclusion

Brazil is one of the leading contributors to climate change, primarily due to the conversion of tropical forests to pasture lands. Land use change currently serves as Brazil's largest source of carbon dioxide emissions, accounting for approximately 35% of the total (SEEG, 2015). At the same time, Brazil has been leading the world in the reduction of greenhouse gasses, balancing the reduction of deforestation with the growth of the agricultural sector (Nepstad et al., 2014). As the nation turns its attention to the contribution of cattle ranching to the release of these gasses, it is important to understand the expected impact of the intensification policies on these objectives. The adoption of these efficiency measures has been supported by industry and promoted by EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária - Brazilian Enterprise for Agricultural Research) in the form of 'Best Ranching Practices' including extension visits, research efforts and programs to improve access to credit. Success in reaching these dual goals to further reduce deforestation while promoting agriculture growth clearly hinges on whether the adoption of intensification practices reduces pressure on forests.

Previous work has suggested that the impact of beef demand on pasture expansion is multifaceted and non-linear (Bowman, 2016). This paper empirically assesses the impact of intensification on the demand for pasture by small-scale farmers in the state of Rondônia and concludes that intensification practices have a non-linear and differential impact dependent upon the modeling choice: the use of intensification practices related to cattle and beef production first increases the demand for cleared land, but as intensification increases eventually the demand for cleared land declines. At the same time, the use of intensification practices related to milk production are in fact related to a reduction in the demand for pasture. The "Boserup Hypothesis" predicts such a complex response. While this paper does not identify the causal mechanisms underlying this relationship (i.e. if intensification is a determinant of future extensification), it is evident that intensification leads to an increase in the pressure on forests for households who focus on calf and beef production. Actually, this result is far from surprising, as previous research on other agricultural policies promoted for their co-benefits have proved "frustratingly elusive" in practice, with studies suggesting that the relationships among these objectives are characterized by substitution effects and not complementaries (Marchand, 2012; Lee and Barrett, 2001; Lee, 2005).

The lure of co-benefits and the ability to simultaneously address climate change while promoting development is what largely guides current low-carbon agriculture programs and climate change objectives in Brazil. This paper shows the reliance on policies that promote intensification is a risky way of achieving climate change objectives. Instead, if these policies were to be combined with limits on the amount of land that can be placed into production, such as a "save-a-hectare" program, which would permanently preserve (in a different location) every hectare that is not deforested due to the adoption of intensification practices, future pressure on forests could be reduced. The forest quota market established as part of the 2012 Forest Code and set to go into effect in 2018 (Soares-Filho et al., 2014), provides a framework for which such a system could be administered. Recent 2012 revisions to the previously unenforced Forest Code reduce the forest restoration requirements, introduce a compulsory rural land registry (a geo-referenced, cadastral database), and provide deforestation amnesty for all small landowners (for land deforested prior to 2008) who register their properties in the rural land registry. As a result, most deforestation in the study area will be forgiven. Households with an environmental plan will continue to be permitted to use their property for pasture, however, this new law (when fully enforced) will place future limits on deforestation on properties not completely cleared by 2008. The impact on future land use and intensification practices relies heavily on the enforceability of these new requirements and standards.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.jeem.2018.06.006>.

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